

The Hawaii K-Band Galaxy Survey. II. Bright K-band Imaging

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Abstract

We present the results of a wide-field K-selected galaxy survey with complementary optical I- and B-band imaging in six fields with a total coverage of 9.8 square degrees. The observations were carried out on the UH 0.6m and the UH 2.2m telescopes. The purpose of this survey is to study the properties of the local galaxies and explore the evolution of K-selected galaxies at low redshifts. Star-galaxy discrimination is performed using both galaxy color properties and object morphologies, and 6264 galaxies are found. This survey establishes the bright-end K-band galaxy number counts in the magnitude range $13 < K < 16$ with high precision. We find that our bright-end counts have a significantly steeper slope than the prediction of a no-evolution model, which cannot be accounted for by known observational or theoretical error. We also argue against the likelihood of sufficient evolution at such low redshifts to account for this effect, we describe an alternative picture in which there is a local deficiency of galaxies by a factor of 2 on scale sizes of around $300h^{-1}$ Mpc. Taken at face value, this would imply that local measurements of Ω_0 underestimate the true value of the cosmological mass density by this factor and that local measurements of H_0 could be high by as much as 33%.

Subject headings: galaxies: evolution – galaxies: photometry – infrared: galaxies

1. Introduction

Near-infrared galaxy surveys (Mobasher *et al.* 1986, Gardner *et al.* 1993, Glazebrook *et al.* 1994, Cowie *et al.* 1994, McLeod *et al.* 1995, Djorgovski *et al.* 1995) have provided extensive information on galaxy evolution. As noted by these studies, a near-infrared selected galaxy sample may provide more advantages in studying galaxy evolution and cosmological geometry than an optically selected sample. Its insensitivity to transient burst of star formation and its small K-corrections even at large redshift simplify our modeling of the galaxy number count-magnitude relation, and can lead to a direct determination of galaxy evolution. The near-infrared K-correction is also insensitive to spectral type, thus a near-infrared selected sample is unbiased with respect to the mix of spectral type. This is very valuable in studying large-scale structure.

Because of the small format of the first generation IR arrays, the early K-band surveys (Gardner *et al.* 1993, Glazebrook *et al.* 1994, Cowie *et al.* 1994) were mainly deep surveys over relatively small areas. After the Keck telescope became available, it became easier to conduct such pencil beam deep K-band surveys (Djorgovski *et al.* 1995). Unlike the B-band number counts, which show a large excess over the no-evolution prediction for the faint-end counts, the K-band number counts established from these surveys do not show such a large excess. However, in order to draw conclusions on the nature of galaxy evolution in these deep samples, it is essential to have extensive knowledge of the local K-band luminosity function and the color distribution of a local K-selected sample and there are few such samples available. The

primary sample used as a local reference was one obtained by Mobasher *et al.* (1986). Their complete K-band sample to $K=12$ was extracted from the B-selected sample. Later a K-band local luminosity function was constructed using this sample (Mobasher *et al.* 1993).

The recent development of large format IR-arrays such as the NICMOS (256×256) and HAWAII (1024×1024) HgCdTe devices, has now made it possible to conduct a large field near-infrared survey. The Hawaii wide-field K-band survey aims to study the local galaxy properties in the near-infrared. With about 10 square degrees coverage and a limiting magnitude of $K=16$, the sample contains 6264 galaxies. This sample will allow us to determine the local galaxy density and the morphological mix of the K-selected local galaxy sample. The current availability of a multi-fibre spectrograph (Taylor 1994) also makes it possible to conduct redshift measurements effectively for our sample. Hence, using this sample we will eventually be able to construct a more precise K-band local luminosity function. In this paper, we will discuss the imaging and photometry of the survey, and define a K-band galaxy number-magnitude relation to $K=16$. We also apply the no-evolution model to the observed galaxy number-magnitude relation and discuss the distribution the local K-selected galaxy density. In the following paper, we will analyze the morphological mix of the K-selected bright galaxy sample up to $K=14$ (Huang & Cowie 1996).

2. Observation and Data Analysis

2.1. Field Selection

The Hawaii wide-field K-band survey consists of two parts. The first part was done in two relatively small areas, totaling about 1.58 square degrees, to a magnitude limit of $K=14.5$. This part of survey yielded a relatively small sample whose redshifts could be easily measured. The data analysis and redshift measurement are given in Gardner(1992) and Songaila *et al.* (1994). We will re-analyze these data together with the second part of the survey.

The second part of the survey, is designed to use the newly-developed multi-fibre spectrograph (the 2DF) on the Anglo-Australian Telescope(Taylor 1994) for followup redshift measurement. Four fields, named SA, SB, SC and SD, were selected on the equator, so as to be observable from both Mauna Kea, Hawaii and the AAO, Australia. These 4 fields avoid rich clusters and very bright stars. We also selected fields on which previous surveys have been carried out. Glazebrook *et al.* (1994) conducted a medium-deep K-band survey on the fields SA, SC and SD with small sky coverage. The fields SC and SD are also sites of the Anglo-Australia Redshift Survey, each with a total of 14 square degrees of coverage (Peterson *et al.* 1986). All four fields are at high galactic latitudes to avoid galactic extinction. After we trim those parts of the areas with insufficient S/N ratio, each field splits into 2-4 pieces and the total number of areas becomes 13. The positions and completeness limits in the K-band are summarized in Table 1.

2.2. Observation and Data Reduction

The observations were carried out on the University of Hawaii telescopes on Mauna Kea, over more than a hundred nights during the 1993-1995 period. The K-band images were taken using the 24 inch telescope with the NICMOS IR camera (256×256 pixels). The field of view of the NICMOS camera on the 24 inch telescope is approximately 8 arcminutes with a scale of 2.02 arcseconds per pixel. Each field was observed frame by frame in the Dec. direction to form a one-degree strip, then each strip was stepped in the R.A. direction. The offset between frames in each strip is about 4 arcminutes, or half field of view. Hence, a strip contains 16 images. The offset between each strip is also 4 arcminutes. Therefore, each pixel was exposed 4 times in total, except those on the edges and corners which were exposed 2 times and 1 time respectively. These edges are trimmed in the final mosaic frames. With a 2 minute exposure time for each single image, the final mosaiced K-band image has an exposure time of 8 minutes. The advantage of this observational pattern is that bad pixels and cosmic rays are easily removed, as we form the final image by taking the median of the 4 counts on each pixel. Instead of using a standard K-filter, we used the K' filter (Wainscoat and Cowie 1992), which is slight bluer than the standard K filter, to avoid the thermal IR emission. The K' filter significantly reduces the sky background. The background of each frame with a 2 minute exposure time is still very high, on average 3000-5000 counts. The background also increases with airmass, so each observation was limited to an hour angle less than 2.5 hours. There are further advantages to the low airmass limitation: it ensures a uniform S/N ratio throughout whole area; and it minimizes the zero point problem due to different airmasses in the final mosaic, since the magnitude difference for the background in our fields between zenith and hour angle of 2.5 hour is less than 0.01. The near-infrared standard stars were taken from the list of Elias *et al.* (1982), with K magnitudes of $6 < K < 9$. We used a linear relation derived by Wainscoat and Cowie (1992) to transfer the K magnitudes of the standard stars to the K' magnitudes. Since the linear dynamic range of each pixel in the NICMOS camera is up to 20000 count rates, the exposure time must be short enough for the standard stars to prevent saturation. We took 5 seconds exposure time for our standard stars. The highest peak count rates of our standard stars are about 12000.

The image processing for the near-infrared images is the same as that used in the Hawaii Deep Survey, described in Cowie *et al.* (1994). We would like to emphasize some important points here again. For the K-band images, the dark current is insignificant, and therefore was not subtracted from each raw data frame. The flat field was created by using the high sky background of the raw data. Due to the variation of the sky OH emission, the sky flat field in K-band may change on time scales of 20–30 minutes (Glazebrook *et al.* 1994). Hence, for each raw K band image, the flat field was generated by using a median filter of ten nearby adjacent frames in the observation time sequence. Since the sky background is so high, the noise is then dominated by the background noise. The flat field generated from ten raw frames should have a lower noise level than the expected final mosaic images which are a median of only four raw images so that the flat field created in this way does not contribute significant noise to the final image.

We were successful in obtaining B and I band photometry of entire area reported in Table 1 covered by the K-band exposures. The observations in I and B band were primarily obtained on

the 88 inch telescope with a Tek2048 CCD. Of the total area for which we obtained the B-band photometry, about 25% was observed with the 24 inch. The purpose of the optical imaging is to separate stars from galaxies in the color-color diagram, and to study the morphology of the K-selected galaxies. With a scale of 0.22 arcsecond per pixel and average seeing of 0.8 arcsecond, the I-band images have much higher spatial resolution than the K-band images. The field of view for the CCD images is about 7 arcminutes at the 88 inch. The observing pattern for the optical observations is similar to that of the K-band observations. The effective exposure time is 2 minutes for the I and B band images taken on the 88 inch telescope, and 20 minutes for the B band images taken on the 24 inch telescope.

The data reduction for the optical images follows standard procedures. Each raw data frame was bias subtracted, and then divided by a flat field. The procedures for obtaining the flat fields for I and B band images are different. For the I band images, the flat field was created in the same way as for the K-band images. Since the I-band sky-background is also high and stable, a sky flat was used in the I-band image processing. Due to the extremely low sky background level in B band, a twilight flat field was used for the B band images.

The final registering of the K-band images is difficult. Due to the inaccurate pointing of the UH 24 inch telescope, the offset between each neighboring frame needs to be determined precisely. Lack of bright stars and the high noise level in the primary frames can make this measurement difficult. We have developed the following method to cope with this problem. The offset between neighboring frames was measured by using bright stars in the overlapping area. Saturated stars were not used in measuring positions. For those frames with no usable bright stars but apparent faint objects above the noise, a cross-correlation function was used in the overlapping area to determine the offset. At this point, there were only 5% of the frames left whose cross correlation functions with their neighbor frames had too low S/N to determine the offset. The first mosaic was constructed without those frames. The position of each frame on the final mosaiced frame was calculated from its offsets to its neighbor frames. The counts for each pixel of the final frame was the median of counts of the 4 exposures, except for those pixels on the edges. The S/N ratio for those fully covered pixels increases by a factor of 2. We roughly estimated the position for the remaining frames by guessing their offsets to the neighbor frames, usually a half of the raw field of view as designed by our observing stepping pattern; then cut out a similar field of view from the first-pass mosaic, where the composite S/N has generally been substantially improved over that of a single neighboring “raw” data frames, and then ran a cross-correlation function with the corresponding frame to be incorporated into the final position. In this second-pass, the peak of the cross-correlation function can be well determined, since one image has an improved S/N ratio usually by a factor of $\sqrt{3} \sim 1.71$. The position of this frame in the final composite, therefore, could be located. The frame was then incorporated into the composite mosaic. Before each frame is added to the composite mosaic, the peak of cross-correlation function between this frame and the composite mosaic is measured again to suppress the growth of errors by random walks. This process was repeated until all the remaining frames that had been omitted from our first-pass composite mosaic were located. Before the final mosaic was generated, an airmass correction for extinction was applied to each

of the original frames.

The registering of the optical images is much easier, since the effective exposure time for the I and B band observation results in images deep enough to have many usable stars. Therefore the position of each CCD image can be determined precisely in the final mosaiced image. The K and B band images are finally registered to the I band images. Due to the large pixel of the K-band images ($\sim 2.02'' \text{ pixel}^{-1}$), the position error of a star between the K-band image and optical images may be as large as $2''$, though the position error between the I and B band images is much smaller. The final three color images were cut into pieces, each with size $7.3' \times 7.3'$ for easy storage and further analysis.

2.3. Detection and Photometry

The object selection was carried out on the registered K-band images. I and B band counterparts can be easily located, allowing for positioning error, at the position where the K-band objects are detected. Since the original low-resolution K-band images were registered to I-band images which had much smaller pixel scales, this procedure tends to smooth the K-band images, and no further smoothing is applied. For the UH 24-inch telescope, there are many factors contributing to the image quality, such as dome seeing, inaccuracy of tracking, and wind shake. The width of the Point-Spread-Function (PSF) on K-band images is slightly larger than the pixel scale. Our detection procedure is similar to Tyson's (Tyson 1988). The criterion for identifying an object on the registered K-band images is that an object must cover an area of at least 12 arcsec^2 down to a K-band surface brightness of $20 \text{ mag arcsec}^{-2}$. This criterion is equivalent to having 3 connected pixels, each having counts higher than 3σ on the K-band images.

The completeness of the sample was tested by using extensive Monte Carlo simulations. We first mimicked the noise according to the real images. Then five bright galaxies with different Hubble types were selected. After rescaling the counts of these galaxies by different factors, we add the simulated noise and ran the detection process to obtain the galaxy detectability as a function of magnitude. We found that, in each field, such functions vary slightly according to galaxy type. The sixth column of the Table 1 gives the median recovery rate at $K=16 \text{ mag}$ for each field, ranging from 70% to 97%.

The method of photometry is very important in analyzing our results, and therefore should be treated very carefully. As many previous studies have indicated that, for a faint galaxy, its isophotal photometry is strongly dependent on redshift and hard to model, we have chosen to use aperture photometry. Because of the low spatial resolution in the K-band images and the large angular size of the bright galaxies, a large aperture is required. An 8-arcsec-diameter aperture is adopted. This aperture magnitude is corrected to 20 arcsec diameter. For bright galaxies, specifically $K < 13$, their sizes are generally larger than 20 arcsec, and corrections of aperture magnitudes for these galaxies are large and variable. For these galaxies, we used

an isophotal magnitude measuring the isophotal magnitude to a surface brightness of 20 mag arcsec². Since these bright galaxies are local, there is little cosmological effect on their isophotal magnitudes.

Since stars and galaxies have different growth curves, their aperture magnitudes were corrected separately. we first classified stars and galaxies by using their morphological indicators measured in the I-band images, which will be discussed in next chapter. Since a bright galaxy is more extended than a faint galaxy, we have to correct the magnitude differently according to its apparent magnitude. Then we divided galaxies and stars into bins according to their magnitudes using a 0.2 mag bin size. The growth curves were measured by using well-isolated stars and galaxies in each of the bins. The star and galaxy corrections in each bin were made from the median of these stellar and galactic growth curves. Due to the variation of the PSF, the corrections for each field are treated separately. Fig. 1 is an example from one field, and it shows that the corrections for galaxies are a function of the apparent magnitude for galaxies. The corrections for stars are not a function of aperture magnitude since they have same PSF at all magnitudes.

For I- and B-band photometry of the K-selected sample the magnitude was measured with the same procedures as for the K magnitudes centered on the position of the objects in that color. Since we have a large aperture (8 arcsec), it makes almost no difference whether we measure the optical magnitude at the position of the K-selected object or the best optical position. If more than one object was found close to the K-selected object within 2 arcsec, the one closest to the position of the K-selected object was used. If nothing was found, a 3σ upper limit was adopted. The optical photometry was performed in exactly the same way as the K-band photometry; except that on the I-band images, an extra parameter, the fourth moment of the radius, was measured on each object for morphological classification. This parameter is defined as

$$r_4 = \frac{\int_0^R f(r)r^5 dr}{\int_0^R f(r)r dr} \quad (1)$$

where $f(r)$ is the flux, and R is the maximum radius for the integral. If R is too large, r_4 can be dominated by noise. We found empirically that the noise can be minimized for r_4 when $R=3$ arcsec.

The same procedure of detection and photometry was run again through the B-band images to obtain the B-band galaxy counts. The detection criterion is still 3 connected pixels with counts 3σ higher than the noise. This criterion transfers to the surface brightness as, 22.86 mag per square arcsec for the images taken with the 24 inch and 24.21 mag per square arcsec for the images taken with the 88 inch. Our Monte Carlo simulation indicates that the completeness is at 20.5 mag for the images taken with the 24 inch and at 22.2 for the images taken with the 88 inch. The morphological index r_4 is calculated on the I-band counterpart. For those galaxies with B magnitude deeper than 20, their K-band magnitudes are generally beyond the limit of our detection. Hence, the star-galaxy classification cannot be conducted on the color-color diagram, and the morphological analysis is the only way to discriminate between stars and

galaxies. However, for those galaxies fainter than $B=21$ mag, their r_4 becomes noisy, so we measure the B-band galaxy counts only to $B=21$ mag.

2.4. Star-galaxy classification

Star-galaxy classification was carried out in two ways: using object morphology and color properties. The r_4 as a morphological indicator is very sensitive to the shape of an object. Stars all have the same r_4 since they all have the same PSF. The r_4 of an extended object, however, must be larger than that of a PSF, since an extended object contributes more light at large radius than does a PSF. However, it has one disadvantage for morphological identification. As mentioned before, r_4 has to be calculated over a high S/N area, so compact galaxies can be misidentified as stars. A different classifying method must then be applied. The color-color diagram has been proved as a good method to discriminate between stars and galaxies (Gardner 1992), since on an I-K vs B-I color-color diagram, stars are clearly separated from galaxies. As Gardner(1992) noted, the separation line is $(B - I) - 2.5(I - K) = -2.0$. We found that this line separates our data well, see Fig.2. With these two methods, our final criteria to identify a galaxy is: that an object has $r_4 > (r_4)_{psf}$ or that an object has $(B - I) - 2.5(I - K) > -2$. Fig.2 shows that both methods are consistent with each other, as almost all morphologically identified galaxies also lie below the separation line in the color-color diagram.

3. K-band Galaxy Number Counts

3.1 Number Counts

The K-band galaxy number counts are shown in Fig.3. Due to the different completeness limits in different fields, the counts on each field were corrected separately, as described in §2.3. The final counts are the average of all fields weighted by their areas. The number counts cover the magnitude range from $K=12$ to $K=16$. The fitted logarithmic slope of our observed counts shown as filled circles on the plot, is $d\log(N)/dm = 0.689 \pm 0.013$ (the Euclidean value is 0.6). The data are also presented in the Table 2. The 1σ errors for the counts in each bin are also shown, and a detailed discussion is given in §3.2. The average field-to-field variation among our 6 fields at each magnitude bin is also listed in Table 2. We found that this variation has a minimum at $K=14.5$ of only 5%. At the bright end, the variation results from the Poisson noise. However, at the faint end this variation may be caused by other factors as discussed in the following text.

In Fig.3, we also show the data from other surveys. Generally the agreement between the surveys is excellent. Our counts at $K=11.75$, 12.25 match the counts of Mobasher *et al.*'s (1986) well. Between $K=12.5$ and $K=15$ our counts are slightly higher than the other counts. In this magnitude range, however, both the Hawaii medium-deep survey(HMWS)(Gardner 1992) and Glazebrook *et al.*'s (1994) survey have much larger error bars. We also note that between $K=15$ and $K=16$ our counts are systematically higher than those of the HMWS. Though the

difference is only about 10%, within the 1σ error bars of the HMWS, this may also be due to the difference between the two photometric systems used. We also note that over the same magnitude range the counts of Jenkins & Reid (1991), HMDS and HDS (Gardner 1992) are all slightly higher than the present data, probably due to their large Poisson noise. Recently, Gardner *et al.* (1996) have also completed a wide-field K-band survey. Their coverage is nearly 10 square degree, about the same size as ours. Their counts in the range $13 < K < 16$ are within 1σ of our counts. However, their counts at the bright end of $K < 12.5$ are higher than ours. We argue that this difference is very likely due to the small sample statistics. The comparison between the observed counts and model predictions will be given in §3.4

3.2 Uncertainty in the Number counts

Three factors contribute to the uncertainty in the galaxy number counts: the Poisson noise, the galaxy distribution and the magnitude error. Understanding such uncertainties is the key to modeling the galaxy number counts, especially in obtaining the normalization factor ϕ_* . We first analyze the uncertainty of the galaxy number counts caused by the Poisson noise and the galaxy distribution. Several authors (Glazebrook *et al.* 1994, Djorgovski *et al.* 1995) have noted the contribution of galaxy clustering to the uncertainty. However, the distribution of large scale structures such as rich clusters and large voids are poorly known. We can only model the uncertainty caused by the galaxy-galaxy correlation which is well known.

We first give the solution of the error caused by galaxy-galaxy correlation. We approach this problem in non-relativistic form. Since the galaxy correlation scale is about $5h^{-1}$ Mpc, the non-relativistic approach gives a good approximation. Here, 5Mpc is corresponding to an angular size of 0.8 degree at a redshift of 0.15, a characteristic redshift of this K-selected galaxy sample. The uncertainty for a galaxy sample (Peebles 1975, Roche *et al.* 1993, Ferguson & Binggeli 1994) in one field can be written as

$$\sigma_i^2 = N_i + 2.24N_i^2 A \Omega_i^{\frac{1-\gamma}{2}} \quad (2)$$

where i means the i th field, Ω_i is its area in unit of square degree, A is the constant in an angular correlation function (Peebles 1980), as

$$A = r_0^\gamma \sqrt{\pi} \frac{\Gamma(\frac{\gamma-1}{2})}{\Gamma(\frac{\gamma}{2})} \frac{\int_0^\infty x^{5-\gamma} p^2(x) dx}{[\int_0^\infty x^2 p(x) dx]^2} \quad (3)$$

$p(r)$ is a selection function, $r_0 = 5h^{-1}$ Mpc, and $\gamma = 1.77$. For a sample with apparent magnitude m ,

$$p(r, m) = \phi(m - 5\log(r) - 25) \quad (4)$$

$\phi(M)$ is the luminosity function. We adopt the Mobasher *et al.* (1993) K-band luminosity function here with $M_* = -23.59 + 5\log(h)$ and $\alpha = -1$. For the observed galaxy number

counts, each bin is a sample with apparent magnitude m . Therefore, by applying equation (4) to (3) to calculate the constant A , then putting (3) into (2), we obtain an analytical solution of the uncertainty in observed galaxy counts at each magnitude;

$$\sigma_i^2 = N_i(m) + 5.3 \left(\frac{r_0}{r_*}\right)^\gamma \Omega_i^{\frac{1-\gamma}{2}} N_i^2(m) \quad (5)$$

and $5\log(r_*) = m - M_* - 25$. $N(m)$ is the observed counts in each bin. The final uncertainty for the number counts per magnitude per square degree in all fields is

$$\sigma(m) = \frac{\sqrt{\sum \sigma_i^2}}{\Omega \Delta m} \quad (6)$$

with Δm as the bin size and Ω as the total area ($\Omega(K < 14.5) = 9.81d^{-2}$ and $\Omega(K > 14.5) = 8.23d^{-2}$). Fig.4 shows the contribution of both Poisson noise and galaxy correlation uncertainty to the total error in this survey. The 1σ errors of the observed counts calculated by using above equations are listed in the third column of Table 2. It can be proved that for a survey with small sky coverage, the uncertainty caused by galaxy correlation is much smaller than the Poisson noise. As we can see in Table 2, the 1σ is less than the field-to-field variation at $K > 15$, but comparable to the field-to-field variation at $K < 15$. Hence, it is very likely that the other factors (rich clusters and large voids) than the Poisson noise mainly contribute to the field-to-field variation at the deep magnitude ($K > 15$) counts.

Magnitude errors may also cause changes of the galaxy number counts. These magnitude error result from two sources, systematic error and random error. In our case, the systematic error is the error in the zero point for the photometry, which in K-band was $\sigma_s \sim 0.05\text{mag}$ between observing runs. This error does not change the slope of $\log(N)$, but shifts the $\log(N)$ in horizontal direction in the count-magnitude diagram. We can transfer this magnitude error to the count error as

$$\frac{\sigma}{N(m)} = \alpha \sigma_s \quad (7)$$

where α is the slope of $\log(N(m))$. If we take the slope of 0.689 and σ_s of 0.05, we obtain $\sigma/N = 3.5\%$, which is less than the field-to-field variation. The final contribution of this systematic error to the galaxy counts will be less than 3.5%, since the final result is the average counts of all observing runs.

Random error in the magnitudes can also change $\log(N)$. In the K-band survey, the sky background counts are much higher than galaxies counts. Hence the random error in the magnitude of a galaxy is mainly caused by the sky background noise. Our Monte Carlo simulation indicates that the random error changes increasingly from 0.01 mag at $K=13$ mag to 0.2 mag at $K=16$ mag. The observed profile of the counts as a function of magnitude is a result of the real profile of the counts convolving with the random error distribution function, which is usually a Gaussian distribution. If the random error σ_r is a constant, we can obtain an analytical solution as

$$\log(N)_{obs} = \log(N)_{real} + 1.15\alpha^2\sigma_r^2 \quad (8)$$

However, we have know the σ_r increases when the K magnitude becomes faint. Though we can not work out an analytical solution in this case, we can qualitatively analyze this problem. As both random magnitude error and intrinsic galaxy counts increase with increasing magnitude, on average there are more faint galaxies erroneously appearing in a brighter bin than brighter galaxies erroneously appearing in a fainter bin. Hence, the observed slope of $\log(N)$ becomes steeper than the real one. This trend can also be seen in above equation. As we consider the slope change in the magnitude range from K=13 to K=16, this range is much larger than the random magnitude error $\sigma_r = 0.2$. By considering that only the galaxies at nearby bins can contribute to erroneously increasing of the galaxy counts, we argue that it is a good approximation to use above equation to estimate the change of the slope as

$$\Delta\alpha = 1.15\alpha^2 \frac{\sigma_{r1}^2 - \sigma_{r2}^2}{m_1 - m_2} \quad (9)$$

As a first order approximation, we use $\alpha = 0.689$, $\sigma_{r1} = 0.2$ at $m_1 = 16$ and $\sigma_{r12} = 0.01$ at $m_2 = 13$ to obtain that $\Delta\alpha = 0.008$ and $\Delta N/N = 5.1\%$ at K=16. Since the 1σ of the slope from fitting is 0.013, this effect does not change the slope of the counts significantly.

4 B-band Galaxy Number Counts

The B-band galaxy counts are presented in Fig.5, together with the data from other surveys. The data are also listed in Table 3. The purpose of measuring the B-band counts is to monitor our fields. Though we carefully selected the fields, we still need to know if there are any special galaxy distribution structures in our fields to distort the galaxy counts. The B-band galaxy counts have been studied substantially, as summarized by Koo & Kron (1992). In the B-band magnitude range (14 - 21 mag) which our counts cover, some survey areas cover as much as 4300 square degrees (Maddox *et. al.* 1990). Our B-band galaxy counts are consistent with the counts of other B-band surveys including Maddox *et. al.*'s survey. This consistency means that our fields are an average field, and the K-band galaxy counts measured from our fields may not be distorted. The physical relation between the K-band counts and the B band counts will be discussed later.

The 1σ error of the B-band counts listed in Table 3 are calculated by using equation 5 and 6 with a set of parameters of a B-band luminosity function. Like the K-band counts, this error is also dominated by the Poisson error. The field-to-field variations for the B-band counts are listed in the third column of Table 3. Our zero point error for the B-band photometry is about 0.03 mag, and the slope of the B-band counts in the range of 15 mag to 21 mag is 0.38. By using equation 7, this systematic error transfer an error of the counts at about 1% level. The random error of the B magnitude is different from that of the K magnitude. Since the B-band sky background is very low, the random error is mainly caused by the photo counting statistics of a galaxy, and is inversely proportional to square root of its counts. Hence, the faint galaxies have larger magnitude errors than the bright galaxies. The random error is only about 0.01 at

B=21 mag, and negligible at B=16 mag. Putting this error and the slope of the B-band counts in equation 9, we find that the steepening effect of the random magnitude is negligible for the B-band counts.

5 Modeling the K-band Counts

5.1 No-Evolution Model

The K-correction is also a key issue in understanding a faint galaxy's magnitude. In the optical bands, the K-correction is a strong function of morphological type (Cowie *et al.* 1994). Thus, in fitting no-evolution models to optical counts, usually measured in the B-band (King & Ellis 1985, Yoshii & Takahara 1988), the mix of morphological type has to be determined. We also have to obtain the type-dependent luminosity functions, which are usually assumed to be the same as for the observed total luminosity function. The no-evolution modeling for the optical counts is, therefore, highly dependent on the mix of morphological types. However, the K-correction in the K-band is different. Firstly the near-infrared spectrum of a galaxy is flatter and more featureless than in optical band so the K-band corrected magnitudes are consequently more reliable than the optical corrected magnitudes. Secondly, the K-correction in the K-band is only a weak function of morphological type. Up to $z=1$, to a good approximation, we can ignore the differences of K-correction in the K-band among different Hubble types (Glazebrook *et al.* 1994). The details of the K-band K-correction, however, are poorly determined. Currently the K-band K-correction is derived either from evolving galaxy models (Rocca-Volmerange and Guideroni 1988, Bruzual and Charlot, 1993, and Buzzoni 1995) summarized by Glazebrook *et al.* (1995a), or from interpolation of the J-K and H-K colors (Cowie *et al.* 1994). The K-corrections derived from these methods, as we see in Fig.6, do not agree with each other exactly. Considering the uncertainties of these methods, however, the differences are reasonable. As seen in Songaila *et al.* (1994), even at their deepest magnitude (K=20) the median redshift of the K-selected galaxies is still substantially less than one. Since our number-counts are below K=16, we can construct a no-evolution model for our K-band counts with a general K-band luminosity function and a simple K-correction term.

The traditional K-band luminosity function (Yoshii & Takahara 1988) is derived in this way: first by assuming that each Hubble type has a uniform color, B-K; then by converting each optical type-dependent luminosity function into K-band type-dependent luminosity function according to color; and finally by adding all type-dependent luminosity functions weighted according to the type mix. More directly, we can just use the observed K-band luminosity function. Unfortunately, the K-band luminosity functions reported in the literature do not agree with each other well. Mobasher *et al.* (1993) conducted a redshift survey on a K-selected subsample from the B-selected sample of the Anglo-Australia Redshift Survey, and constructed the first K-band luminosity function fit to a Schechter function with $M_* = -23.59$ ($h = 1$ hereafter) and $\alpha = -1$. The K-band luminosity function which Glazebrook *et al.* (1995a) obtained directly from their K-band survey has a similar shape, but their M_* is significantly fainter, $M_* = -22.75$. The most recent determination of Cowie *et al.* (1996) finds an M_* consistent

with that of Mobasher *et al.* (1993) and a similar shape. Both luminosity functions will be used in constructing the no-evolution model.

The no-evolution model can also be presented in another way, as a mean color-magnitude relation. Specifically, we will derive $\langle I - K \rangle$ as a function of K magnitude. Due to the difference of the I-band K-correction for different spectral type galaxies, the $\langle I - K \rangle$ of each type of galaxy has to be treated separately. Since we do not have the K-band type-dependent luminosity function we have to adopt the general K-band luminosity function for each type galaxies. To be consistent with the I-band K-correction in Cowie *et al.*'s paper (1994), we simply divide galaxies into E/SO, Spiral, Irregular galaxies, and adopt the I-band K-correction directly from their paper. Then, for each classified type galaxies, we have

$$\langle I - K \rangle = \langle I - K \rangle_{z=0} + \frac{\int n(z, m)(kc_i(z) - kc_k(z))dz}{\int n(z, m)dz} \quad (10)$$

where $n(z, m)$ is the no-evolution model of the galaxy counts as a function of redshift and magnitude, kc_i and kc_k are the I and K band k-correction terms. In Fig.7, the models of $\langle I - K \rangle$ for E/SO, Spiral, Irr are plotted in comparison with the observed data. Each model has been normalized to the colors of the bright galaxies whose morphologies in their CCD images are classified by authors. The models with faint M_* predict bluer colors at the faint magnitude end than those with bright M_* . This is because, for a flux limited sample, a model with faint M_* predicts fewer distant galaxies than a model with bright M_* , and the I-band K-correction makes the color of distant galaxies redder than those of nearby galaxies. The observed $\langle I - K \rangle$ lies between the models of E/SO and Spiral galaxies with the same trend as those of the models. This indicates that the galaxies in the K-selected sample are mainly E/SO and early type Spiral galaxies, and a no-evolution model is good enough to fit the observed color. To combine our models to fit the observed data suggests that, in the K-selected galaxy sample, about 50% of them are E/SO, another 50% are Spiral galaxies, and there are very few irregular galaxies.

5.2 Local K-selected Galaxies

Understanding the local galaxy sample is also essential in connecting the model to the observed counts, since the local galaxy sample serves as a reference point for the models. We selected a subsample with a limiting apparent magnitude of K=15 mag. If we also add the counts of Mobasher *et al.* (1986), the local counts cover from K=10 to K=15. For such a magnitude range, a no-evolution model can be characterized by its slope. We have calculated the slopes of no-evolution models with different luminosity functions, different geometries, and different K-corrections. The slope of a no-evolution model in $10 < K < 15$ is independent on q_0 , and varies only from 0.605 to 0.623, for all current varieties of M_* and the K-correction. The result is summarized in Table 4. We conclude that the slope is very weakly dependent on the M_* , and the difference in the current K-corrections does not significantly change the no-evolution model. The slope of the observed counts at this magnitude range, however, is

much larger than the maximum slope of the theoretical prediction. As shown in Fig.8, the slope of the counts in this survey is 0.69 ± 0.014 . When we combine our counts with those of Mobasher *et al.*'s (1986), the slope becomes 0.68 ± 0.012 . Gardner *et al.* (1996) obtained a flatter slope, as 0.63 in $10 < K < 16$. However, by excluding their bright counts measured with only a few galaxies, their slope in $13 < K < 15$ is 0.65, which is not as steep as ours. It is possible that their fields contain more bright galaxies than the average, since their B-band counts below $B = 18$ are significantly higher than the B-band counts of Maddox *et al.* (1990). By combining our counts with Gardner *et al.*'s (1996), we still obtain a much steeper slope of 0.67 in $13 < K < 15$. Hence the no-evolution model slopes are $5\sigma - 7\sigma$ away from the observed slope. Normalizing our no-evolution model with the steepest slope to the counts at $K=10.25$ as in Fig.8, we find that the model can not fit the observed counts. The result is independent of our selection of luminosity functions, normalizations and geometries. The only parameter that determines the slopes of no-evolution models is the K-correction. Though the K-corrections derived from various methods are quite consistent with each other as we indicated above, they could be still poorly determined. Near-infrared emission features could be missed in the stellar synthesis models and the color interpolation. The features in between $2.0\mu m$ to $2.2\mu m$, such as He I, H_2 S(1), and Br γ could change the K-correction at low redshifts, and therefore change the slope of a no-evolution model in $10 < K < 15$. We found that we could fit the number counts by artificially increasing the K-correction by a factor of 3 at between $z=0$ and 0.2. However, we argue that such a large correction (more than a magnitude) is very unlikely to be the case. Ridgway *et al.* (1994) took near-infrared spectroscopy on their infrared-luminous galaxy sample. Most of the galaxy spectra in the range of $2.0\mu m$ to $2.2\mu m$ are featureless, even if where the infrared-luminous galaxies are gas-rich galaxies. Our K-selected sample is dominated by early type galaxies, and cannot have such strong emission features. Hence we do not think that the current K-corrections can deviate from the real one by such a large factor. The difference between the observed counts and the model prediction at $13 < K < 15$ implies either galaxy evolution at low redshifts or a local deficiency of galaxies.

Galaxies with apparent magnitudes of $13 < K < 15$ are located at $z < 0.2$ (Songaila *et al.* 1994). Galaxy evolution at such low redshifts was first proposed based on the B-band counts (Maddox *et al.* 1990). Maddox *et al.* found that there was an excess in their B-band counts at $18 < B < 20$ over a no-evolution model. Their magnitude range in the B-band is equivalent to $13 < K < 15$ in the K-band. Such galaxy evolution, however, is very unlikely to be luminosity evolution since many redshift surveys (Cowie *et al.* 1996, Ellis *et al.* 1996, Glazebrook *et al.* 1995a, Songaila *et al.* 1994) in both B-band and K-band have shown that galaxies with luminosities brighter than L_* ceased evolving long before $z=0.5$. The galaxy evolution at low redshifts suggested by some of these authors occurs only among low luminosity galaxies. By analyzing K-band and B-band luminosity functions at different z (Cowie *et al.* 1996, Ellis *et al.* 1996), they found that there were more dwarf galaxies in the past than now. Cowie *et al.* (1996) further suggest that higher density of dwarf galaxies in the past is due to the evolution of the formation process. However, this evolution is not significant at $z < 0.2$. We will be able to confirm this argument only after we compare the luminosity functions at $z=0$ and at $z=0.2$, constructed from this sample in the followup redshift survey.

A local deficiency of galaxies seems the best explanation of the steep counts at the bright-end. This possible explanation has been proposed based upon the B-band counts (Shanks 1989 and Driver *et al.* 1995) and radio source counts (Windhorst *et al.* 1990, Condon 1989). The model requires that the Galaxy happens to be in an extremely large low-density region in the universe with a scale from $300h^{-1}$ Mpc to $600h^{-1}$ Mpc (corresponding to $z = 0.1 \sim 0.2$). The galaxy number density of our neighborhood is then lower than the galaxy number density at $z = 0.1 \sim 0.2$ which may be the true average galaxy number density of the universe. The difference between the observed counts and the no-evolution model at $13 < K < 15$ normalized at $K=10.25$ then represents the difference between the density of our neighborhood and the average density of the universe. We find that the following function of $\phi_*(z)$ can increase the slope of a no-evolution model at $K < 15$ to 0.69 (see Fig.8);

$$\phi_*(z) = \phi_*(1 + \exp(-(z/0.1)^2))^{-1} \quad (11)$$

This function is almost constant at $z > 0.2$, and so does not significantly change a no-evolution model at $K > 16$. This density profile is very arbitrary, since the observed galaxy counts provide little constraint. However, this function should also fit the B-band bright counts if there is a real local deficiency. From the B-band bright galaxy surveys (Shanks 1989 and Maddox *et al.* 1990), we already know that the slope of the B-band bright counts below $B=20$ is steeper than that of a no-evolution model. Fig. 5 shows the observed B-band counts (including ours) and the no-evolution model made by Ellis (1987). Furthermore, our local hole model predicts that the galaxy density at $z=0.2$ is twice the local galaxy density at $z=0$. When Shanks (1989) normalized his B-band no-evolution model at $B=18$, the model indeed over-predicted the local galaxy density by a factor of 2. Maddox *et al.* (1990) also found that their B-band counts at $B=20$ had an excess over the no-evolution model by a factor of 2. As many redshift surveys indicate, galaxies with $B = 18 \sim 20$ are located at about $z=0.2$. Thus, the B-band counts show a similar density profile to that of the K-band counts. This indicates a consistency for the local deficiency model. However, since we also do not know exactly where galaxies stop evolving, a redshift survey on a very large bright sample, such as this large K-selected sample, is required to distinguish these two effects on the steep counts at bright-end. Such a redshift survey will be large enough to provide precise luminosity functions at different redshifts. If the shape of K-band luminosity functions in this redshift range remains the same, but ϕ_* changes with z , this will confirm that the large scale structure produces the steep slope at the bright end of the observed counts.

Voids and superclusters are the largest structures ever found in the universe (Rood 1988, Bahcall 1988). Their scales are usually from $20h^{-1}$ Mpc to $120h^{-1}$ Mpc. Since the previous large redshift surveys have limited depth, no structure with a scale larger than $200h^{-1}$ Mpc has been yet discovered. The presence of a local low-density region with a scale larger than $300h^{-1}$ Mpc must have a fundamental effect in our measurement of H_0 and Ω (Turner *et al.* 1992). It implies that local measurements on smaller scales may overestimate the “true” value of H_0 by as much as 33% and underestimate Ω_0 by a factor of 2. If true, this would go far to resolve current time scale problem at the expense of introducing extraordinarily large scale

inhomogeneity into the cosmological model.

6. Conclusion

We have completed a K-band field galaxy survey with a total coverage of about 10 square degrees. The results are summarized below.

(1) The K-band counts from this survey extend from $K=12$ to $K=16$. They are well matched to the counts of other surveys in this range, but have much smaller error bars than previous studies.

(2) For a pencil-beam survey, the error caused by galaxy-galaxy correlation is smaller than the Poisson noise. At the faint end of our counts, the error is dominated by the large scale structures.

(3) We construct no-evolution models for the K-band counts by using a variety of luminosity functions, geometries and K-corrections. In the range of $10 < K < 15$, these models yield very similar predictions.

(4) The shape of the bright-end counts does not fit no-evolution models. We find that none of the theoretical and observational uncertainties that we have been able to identify can cover this discrepancy. We, then, conclude that there are changes in the galaxy luminosity function at low redshifts for a K-selected sample. The steep slope may be due to a change in ϕ_* with redshift, which reflects a substantial local deficiency of galaxies over scale sizes of $300h^{-1}$ Mpc. This would imply that the universe is inhomogeneous on extremely large scales and that local measurements overestimate H_0 by factors of up to 33% and underestimate Ω_0 by a factor of roughly 2. The conclusion needs to be confirmed by the follow-up redshift survey.

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FIGURE LEGENDS

Figure 1 This is an example of the magnitude correction on one of our fields. We correct the aperture magnitudes of faint objects ($K > 13$) to 20 arcsec diameter. The correction ΔM is a function of the aperture magnitude for galaxies, but not for stars. The solid line shows the correction for galaxies, and the dashed line for stars.

Figure 2 This is an example of star-galaxy classification in one field. The star-galaxy Classification is performed in the (B-I) vs (I-K) color-color diagram. The line marks the bounding color criterion for separating stars and galaxies (Gardner, 1992). The cross mark represents an objects with $r_4 > (r_4)_{psf}$, and the dot mark represents an objects with $r_4 = (r_4)_{psf}$. The diagram shows that morphological and color criteria match very well.

Figure 3 The filled dots are the counts from this survey. GAR: Gardner *et al.*, (1996); MCL: McLeod *et al.*, (1995); HDS: Hawaii Deep Survey (Gardner, 1992); HMDS: Hawaii Medium Deep Survey (Gardner, 1992); HMWS: Hawaii Medium Wide Survey (Gardner, 1992); JR: Jenkins and Reid (1991); GLZ: Glazebrook *et al.* (1994); DJO: Djorgovski *et al.* (1995); MOB: Mobasher *et al.* (1986). The $d(\log(n))/dm=0.69$ for the counts from this survey. The error bars of our counts are calculated by using equation 5 and 6 with a K-band luminosity function

Figure 4 The errors in our number counts are calculated from Equation (6). It is shown that the error caused by the galaxy-galaxy correlation is smaller than the Poisson error. We have $\sigma^2 = \sigma_{poisson}^2 + \sigma_{cluster}^2$, then, for a pencil-beam survey, the clustering error is not important.

Figure 5 Our B-band galaxy number counts are plotted with the no-evolution model (Ellis, 1987). The counts of other surveys plotted here are those of Gardner *et al.* (1996) ($10deg^{-2}$), Shanks *et al.* (1984), Heydon-Dumpleton *et al.* (1989) ($100deg^{-2}$), and Maddox *et al.* (1990) ($4300deg^{-2}$). The error bars of our counts are calculated by using Equation 5 and 6 with a B-band luminosity function

Figure 6 The K-corrections are plotted. The Solid line is the mean K-correction of all type galaxies from the JHK interpolation; the dotted line is the k-correction from Bruzual and Charlot (1993); the dashed line is the K-correction from Rocca-Volmerange and Guiderdoni (1988). The K-band K-corrections of the different type galaxies are very similar at low redshifts. Therefore we only plot their means here.

Figure 7 The left panel is the plot of I-K vs K. In the right panel, the models of $\langle I - K \rangle$ are plotted with the observed data. The upper lines are the models of E/SO galaxies; the middle lines are the models of Spiral galaxies; and the lower lines are the models of Irregular galaxies. The solid lines are the models with the luminosity function of Mobasher *et al.* (1993), and the dashed lines are the models with the luminosity function of Glazebrook *et al.* (1995a). The difference of these two models is discussed in the text.

Figure 8 The K-band galaxy counts are fitted by a pure no-evolution model (solid line) and a no-evolution model with a density gradient (dashed line). It is clear that the slope of a pure no-evolution model is very different from that of the observed counts. The crosses are the counts of Mobasher *et al.* (1986); the filled dots are the counts of this survey; and the triangles are

the counts of Gardner *et. al.* (1996). Our fitting does not include the counts of Gardner *et. al.* (1996). However, their counts match our model very well in $13 < K < 15$.

Table 1: Position and Completeness of Fields

name	$\alpha(1950)$	$\delta(1950)$	b	Area(d^2)	P_{16}^a
SSA13 ^b	13:10:01.7	43:00:33	74	0.84	—
SSA17 ^b	17:04:59.8	43:59:35	37	0.74	—
SA	22:42:57.6	-00:28:12	-49	0.46	0.97
SA	22:41:00.9	-00:27:40	-49	0.15	0.97
SA	22:39:10.8	-00:29:23	-49	0.84	0.72
SB	03:43:32.3	-00:30:21	-41	0.34	0.92
SB	03:38:57.7	-00:29:40	-41	1.63	0.92
SB	03:43:55.0	00:26:49	-41	0.14	0.70
SB	03:42:39.8	00:29:19	-41	0.35	0.72
SC	10:41:23.8	-00:27:46	49	1.72	0.96
SC	10:43:29.7	00:28:49	49	0.30	0.96
SD	13:41:56.3	-00:25:49	60	0.82	0.96
SD	13:37:58.9	-00:25:46	60	0.74	0.96
SD	13:43:11.8	00:28:52	60	0.32	0.96
SD	13:42:10.2	00:28:56	60	0.42	0.96

a: P_{16} is the recovery rate of a galaxy with $K=16$.

b: These two fields are from Gardner(1992) and Songaila *et al.*(1994) with completeness at $K=14.5$.

Table 2: K-band Galaxy Counts

K	N ^a	σ ^b	$\sigma_{ff}(\%)^c$
11.25	0.2	0.2	
11.75	1.0	0.5	
12.25	2.5	0.7	68
12.75	7.1	1.3	36
13.25	14.5	1.9	41
13.75	30.0	2.7	18
14.25	65.4	4.2	10
14.50	99.2	7.6	5
14.75	157.5	9.8	7
15.00	224.1	11.8	13
15.25	321.4	14.3	11
15.50	495.9	18.5	21
15.75	634.9	21.1	10
16.00	825.1	24.3	15

a: N is in unit of $mag^{-1} d^{-2}$.

b: σ is calculated by using Eq. (5) and (6).

c: σ_{ff} is the ratio of the field-to-field variation to the number counts.

Table 3: B-band Galaxy Counts

B	N ^a	σ ^b	$\sigma_{ff}(\%)^c$
15.0	0.5	0.2	20
15.5	0.8	0.4	32
16.0	2.3	0.8	11
16.5	3.3	0.8	7
17.0	9.5	1.6	19
17.5	13.6	1.9	13
18.0	26.2	2.6	6
18.5	49.9	3.6	8
19.0	83.6	5.6	7
19.5	171.5	8.0	8
20.0	315.4	13.5	7
20.5	596.0	18.7	7
21.0	931.1	23.3	5

a: N is in unit of $mag^{-1} d^{-2}$.

b: σ is calculated by using Eq. (5) and (6).

c: σ_{ff} is the ratio of the field-to-field variation to the number counts.

Table 4: Slope of No-Evolution Models

M_*	-23.59	-22.75
kc ^a	0.602	0.605
kc ^b	0.617	0.623
kc ^c	0.611	0.618

a: the k-correction of Bruzual & Charlot (1993)

b: the k-correction of Rocca-Volmerange & Guiderdoni (1988)

c: the k-correction of Cowie *et. al.* (1994)















